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Evaluation of control strategies for different smart window combinations using computer simulations

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Abstract

Several studies have shown that the use of switchable windows could lower the energy consumption of buildings. Since the main function of windows is to provide daylight and visual contact with the external world, high visible transmittance is needed. From an energy perspective it is always best to have the windows in their low-transparent state whenever there are cooling needs, but this is generally not preferable from a daylight and visual contact point of view. Therefore a control system, which can be based on user presence, is needed in connection with switchable windows. In this study the heating and cooling needs of the building, using different control mechanisms were evaluated. This was done for different locations and for different combinations of switchable windows, using electrochromic glazing in combination with either low-e or solar control glazing. Four control mechanisms were investigated; one that only optimizes the window to lower the need for heating and cooling, one that assumes that the office is in use during the daytime, one based on user presence and one limiting the perpendicular component of the incident solar irradiation to avoid glare and too strong daylight. The control mechanisms were compared using computer simulations. A simplified approach based on the balance temperature concept was used instead of performing complete building simulations. The results show that an occupancy-based control system is clearly beneficial and also that the best way to combine the panes in the switchable window differs depending on the balance temperature of the building and on the climate. It is also shown that it can be beneficial to have different window combinations for different orientations.

Keywords: Smart windows; Energy simulations; Control strategies; User presence; Solar energy; Building simulations

1. Introduction

The use of fossil fuels passed biomass as the main energy source at the end of the 19th century and has been steadily increasing since then. This is not a sustainable condition and the fact that there is a limited supply of oil, coal and natural gas in the world (Aleklett and Campbell, 2003); together with the recent global warming issue, makes it necessary to completely reconsider our present energy consumption habits. The building sector offers the largest potential for improved energy efficiency in Europe and 30–40% of all primary energy in the world is used for buildings. Windows are the least insulating part of the thermal envelope and therefore a key component for achieving reduced energy consumption in buildings (United Nations Environment Programme, 2007).

A proper choice of windows can help to reduce both heating and cooling needs by reducing heat losses and solar heat gains through the windows. Depending on continuously varying climate conditions, the windows should preferably have a high solar heat gain when there is a need for heating and a low solar heat gain when there is a need for cooling. This can be achieved by external shading such as awnings, but such a solution might have drawbacks, for example sensitive mechanical parts, reduced outside view and outside aesthetics and mounting problems. Thus the emerging technology for switchable, usually electrochro-

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mic, windows provides an obvious opportunity to save energy in buildings. The purpose of a window is not only to let in light and create visual contact with the surroundings, but also to give a comfortable indoor climate and to minimize energy use.

The link between low energy use and good visual and thermal comfort is therefore a control system, where the windows are optimized for personal comfort when someone is present and for low energy use when nobody is present. When someone is present in a room the windows should be light enough to give a comfortable light level in the room, while still avoiding annoying glare. Whenever the room is unoccupied the window can be low-transparent if there is a need for cooling and high-transparent if there is a need for heating. Unfortunately the two requirements of energy optimization and occupancy comfort are not always in agreement. It is therefore also important to acknowledge that any control system should always have an override switch for privacy and individual comfort of the occupants.

The dominating switchable technology today is based on electrochromic coatings where a low voltage is applied between two transparent conductors with intermediate layers that switch between a low-transparent absorbing state and a high-transparent state upon injection or rejection of charged ions into the active electrochromic coatings (Granqvist, 1995). The mechanism is similar to that of a rechargeable battery.

The electrochromic layers can be laminated between two glass panes, laminated between two plastic flexible foils or coated on one of the glass surfaces. All three technologies are in principle related and they have their advantages and disadvantages, depending on the application strategy. With the current trend of energy conservation, it is far from sufficient to introduce efficient technologies in new buildings, it is also absolutely necessary to drastically reduce the energy consumption in older buildings. In this respect the flexible foil technology has an advantage as it can be introduced in existing windows without replacing any of the window frames.

Several simulation studies on smart windows have been performed earlier with various approaches. See for example Lee and Tavil (2007), Assimakopoulos et al. (2004) or Karlsson (2001). The aim of this study was to investigate to what extent different control strategies that were developed for a window energy balance simulation tool, Winsel, can be used to evaluate different window combinations and to see how the different control strategies affect the energy use (Karlsson et al., 2001). This was achieved by investigating how a control system can be configured and how this affects the energy balance of the window under different assumptions, and also by investigating how different window combinations perform together with the different control strategies in various climates and for different orientations.

2. Method

The optical properties of the windows were calculated using a combination of the Fresnel formalism and experimental data. The international standards International Organization for Standardization (2003) and European Comittee for Standardization (1998) were used to calculate the solar factor (g-value) and the thermal conductance (U-value), respectively. For the electrochromic layers, refractive indices were taken from Windows Daylighting Group (2009). The refractive indices were used together with Fresnel formalism to determine the transmittance and reflectance of the complete windows that were "constructed". The choice of electrochromic windows is thus based on simulations, rather than on actual products. This is, however, no limitation since the main objective of the study was to investigate the method and to compare different strategies, not to evaluate the performance of actual products.

The window surfaces are labeled 1–4 from the outer surface to the inner surface according to common practice. Only double paned windows were considered in this study, although in the future it is quite possible to see more of triple glazed windows in high performance low energy buildings. Four double pane reference windows were identified: A window without any coatings, two windows with low-e coatings on surface 3, one with a tin oxide coating and one with a silver based coating, and finally a window with a silver based solar control coating on surface 2.

These reference windows were then combined with electrochromic coatings forming another set of 6 different windows: The uncoated double pane window and the two low-e windows were combined with an electrochromic coating on surface 2. The solar control window was combined with an electrochromic coating on surface 3 and also modified so that the electrochromic coating was on surface 2 and the solar control coating on surface 3. In addition a solar control window with both the electrochromic layer and the solar control layer on the outer pane was designed. The different window combinations are summarized in Table 1 and presented schematically in Fig. 1. All the investigated electrochromic windows can be manufactured with known technologies.

The window simulation tool Winsel was used to estimate the energy balance of these switchable windows, also known as smart windows, when they are installed in a building. The software tool calculates the contribution from the window to the energy balance of the building, without having to know the total consumption of the whole building. It takes solar heat gain into account in combination with thermal losses or thermal gains through the window. For this the program uses outdoor temperature, direct and diffuse solar radiation and calculates energy losses and solar gain using U and g-values, respectively, as input. The building is simulated through its balance temperature and a time constant for heat capacitance. The balance temperature of a building is defined as the outside temperature below which the building needs heating. It depends on the U-value of the building envelope and the internal energy loads. The balance temperature for cooling is in the same way defined as the outside temperature above which the building needs cooling.

Table 1
Optical and energy related parameters for the windows simulated. A_1 and A_2 are the absorption in the outer and inner pane respectively.

Window	Short name	EC coating	T_{sol} (%)	R_{sol} (%)	Δ_{sol} (%)	A_1 (%)	A_2 (%)	T_{vis} (%)	R_{vis} (%)	U (W/m^{2}K)	g-Value (%)
Double pane reference	DG	No	69	13	18	10	7.4	80	15	2.8	75
Double pane EC	DG + EC	Light	59	10	31	25	6.0	74	11	2.8	65
combination		Dark	11	8	81	79	1.3	12	7.7	2.8	18
Low-e reference 1	LE1	No	59	16	25	11	15	74	18	1.6	71
Low-e EC combination 1	LE + EC1	Light	51	11	38	26	12	68	13	1.6	63
		Dark	9.3	8.2	82	80	2.8	11	7.8	1.6	17
Low-e reference 2	LE2	No	52	23	25	12	13	77	13	1.3	64
Low-e EC combination 2	LE + EC2	Light	46	13	41	27	13	71	10	1.3	59
		Dark	8.1	8.5	83	81	2.9	11	8	1.3	15
Solar control reference 1	SC	No	34	41	25	22	2.4	63	25	1.3	38
Solar control EC	SC + EC1	Light	31	40	29	22	7.0	58	23	1.3	38
combination 1		Dark	5.1	41	54	22	32	9.2	24	1.3	33
Solar control EC	SC + EC2	Light	31	29	40	33	7.8	58	18	1.3	39
combination 2		Dark	5.1	9.5	85	84	1.4	9.2	5.3	1.3	11
Solar control EC	SC + EC3	Light	29	26	45	43	1.9	55	23	1.3	33
combination 3		Dark	4.7	9.8	85	85	0.3	8.5	10	1.3	10

Thus, the solar heat gain is only considered a real gain during the heating season and assumed to cause overheating only during the cooling season. Complete building simulations can give more accurate results, but the simplified approach using Winsel gives sufficiently reliable results for the purpose of this study.

For the energy calculations in this study an office building with 8 °C as the balance temperature for heating and 14 °C as the balance temperature for cooling was selected. The energy simulations were performed for three different locations with completely different climatic conditions: Miami with large cooling needs, and non-existing heating needs, Stockholm with large heating needs and with moderate cooling needs and Denver where both heating and cooling needs are moderate. Weather data were taken from Meteotest (2003).

Four different control strategies were considered:

"Energy optimization" means that the windows are always kept in the state that is best from a heating and cooling perspective, while neglecting the energy used for electric lighting. In the simulations the windows are kept in a low-transparent state whenever there is a need for cooling and in a high-transparent state whenever there is a need for heating.

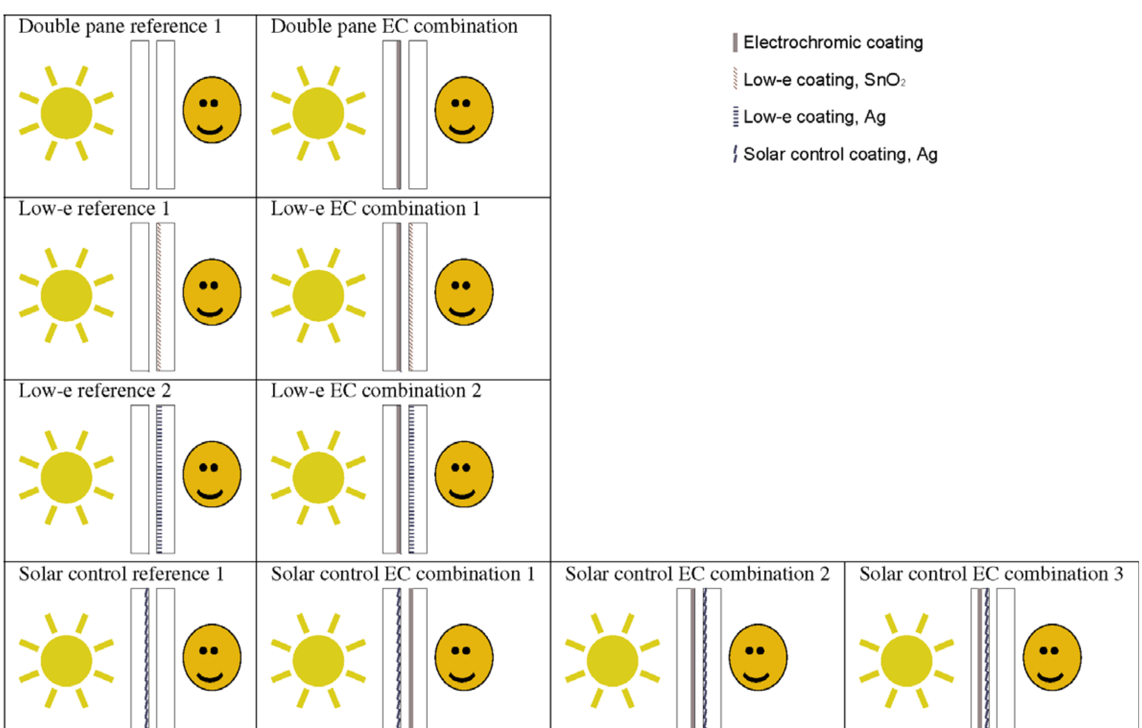

Fig. 1. Figures of the different window configurations that were investigated.

"Daylight optimization" means that the windows are in a state which is optimized from a daylight perspective. In the simulations this was defined as when the perpendicular component of the transmitted direct solar radiation was regulated by the electrochromic coating in the window to a maximum of 200 W/m^2, but can easily be varied to any other value. This mode of the control mechanism reduces annoying glare when the sun is low in the sky and when the solar irradiation is close to perpendicular to the window. Solar radiation at glancing incidence angles does not force the window into a low-transparent state.

"Office 1" mode corresponds to having the window in "daylight optimization" mode between 7:00 a.m. and 6:00 p.m. and otherwise in "energy optimization" mode.

"Office 2" mode corresponds to having the window in "daylight optimization" mode during half of the time between 7:00 a.m. and 6:00 p.m. on weekdays and otherwise in "energy optimization" mode. The different modes are used evenly throughout the day and deviations during certain days are assumed to even out over the year. This is a simplified way of simulating the fact that the office is occupied during only 50% of the time.

The values of 200 W/m^2 for transmitted radiation in the "daylight optimization mode" and 50% occupancy in the "office 2" mode are selected as examples. In the simulations these can easily be adjusted to any value regarded as suitable for the actual function of the building and size and shape of the room. The objective of the study was to compare different strategies and to illustrate that a simplified approach can be quite sufficient for investigating the benefit of using a certain product under certain conditions, and not for calculating the actual energy consumption.

3. Results

The optical and energy related parameters used in the energy simulations can be seen in Table 1. Although all calculations in this study only use the *g*- and *U*-values, an interesting factor to consider is the absorptance values for the different window combinations. The solar control EC combination 1 has absorptance values of less than 33% in both panes. All other EC combinations have absorptance values of about 80% in the electrochromic pane when the window is in its low-transparent state. This might be an important factor in a real design case when the maximum temperature of the window pane that can be reached is considered.

For the energy simulations it is important to note that the results show the cooling and heating needs caused by the windows only. The influence of the rest of the building is assumed to be the same, independent of which window is used. This is in some cases an approximation since it is possible that the choice of window does affect the balance temperature of the building. In this investigation the introduction of the EC-coating does not change the *U*-value of any of the windows, and thus the balance temperature is unaffected. It should also be noted that in all the results graphs shown in the following, the energy is given in units of kWh/m^{2}a, where square meter refers to window area, not floor area. The notation a means per year (annum), but should really be interpreted as the "heating season" and "cooling season", respectively. The different symbols (square, diamond, triangle, plus, cross and dot) in the figures represent different windows. The different colors on the abscissa scale represent different optimization modes connected with solid lines while black refers to the corresponding static cases connected to the other with dashed lines. The dots represent independent case studies and the interconnecting lines are not functions. The connecting lines between the dots in the figures are only guidelines for the eye to connect data points belonging to the same type of window.

3.1. Miami climate

3.1.1. Cooling energy balance

In Fig. 2 the cooling energy balance for the office building was calculated for the climate of Miami. The graph shows the amount of cooling energy caused per square meter of window area during the cooling season. The need for cooling is mainly caused by the solar heat gain through the window and only to a small extent by the thermal energy conducted into the building when the outdoor temperature is higher than the indoor temperature, although this is also taken into account. The negative values simply indicate that it is an energy cost. It is the extra amount of energy, due to the window, that has to be removed from the building by the air-conditioning system in order to maintain the set indoor temperature. The calculations were performed for north, east, south and west facing windows as indicated. For each orientation and window combination the four points on the left correspond to the control strategies according to the indicated color code, and the points in the column furthest to the right correspond to the four reference windows without EC coatings.

As can be seen in Fig. 2, the electrochromic windows always yield a lower need for cooling than the corresponding static alternatives. The most important factor is the control strategy, however. The use of electrochromic

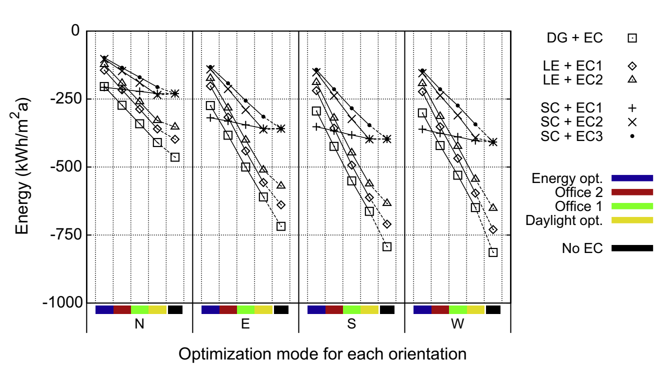

Fig. 2. Cooling energy balance of the studied window combinations in Miami for different orientations.

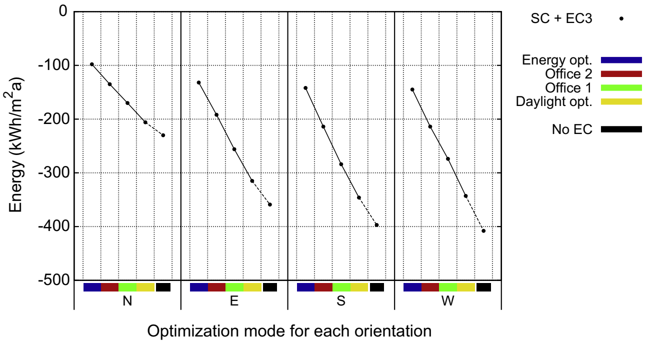

Fig. 3. Cooling energy balance of the solar control window SC + EC3 in Miami for different orientations and control strategies.

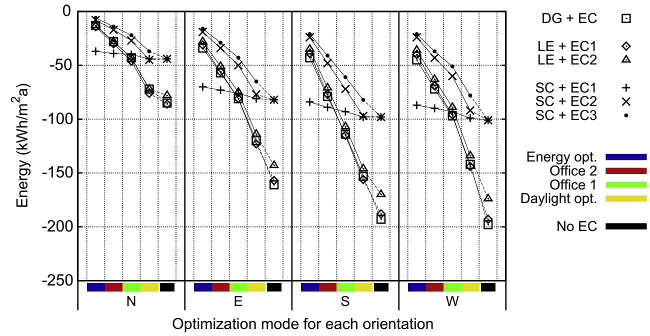

Fig. 4. Cooling energy balance of the studied window combinations in Stockholm for different orientations.

windows in daylight optimization mode reduces the need for cooling by less than 100 kWh/m^{2}a. But if used in "office 2" mode, assuming presence detectors, the reduction could be as high as 200 kWh/m^{2}a. In all cases the energy optimization mode is always the best. This is a necessary outcome of the simulation and is included to show the limits that can be reached with the electrochromic windows. A more realistic strategy in a real situation is probably one of the two "office" strategies.

The graph in Fig. 2 contains a lot of information. For instance, it can be seen that the window combination yielding the lowest need for cooling energy is SC + EC3. The lowest need for cooling energy does not necessarily coincide with the lowest total energy need. The need for artificial lighting can be different depending on which window is used.

In Fig. 3 the best window combination is shown for all orientations and for the different control strategies. It is clearly seen how important the choice of control strategy is for the final result. The improvement for the daylight optimization mode compared to the static window is only moderate. Of course it must be remembered that the outcome of the daylight optimization mode depends on the choice of radiation limit.

3.2. Stockholm climate

3.2.1. Cooling energy balance

The Stockholm climate is quite different from the Miami one, as the heating season is considerable. In fact for the chosen building, the heating and cooling needs are of a similar order of magnitude. Of course the need for cooling is considerably lower than for Miami, but as can be seen in Fig. 4, the trends are the same. Electrochromic coatings on low-e double pane windows would reduce the cooling needs by up to 125 kWh/m^2 annually using "office 2" mode on a south-facing window. It should be remembered that it has not been considered that it is possible to reduce cooling needs by extra ventilation and open windows during times when the outdoor temperature is lower than indoors. It is, however, particularly interesting to note that for all orientations and the most efficient control strategies, the need for cooling energy is almost reduced to zero. This would mean that air-conditioning would not be needed if smart windows were fully utilized.

3.2.2. Heating energy balance

For the climate of Stockholm it is necessary to consider the heating season. Traditionally heating is a more important issue than cooling, although recent developments in building technology and an increased internal heat load owing to computers and office equipment have led to a situation where cooling is becoming more important. In fact an increasing use of air-conditioning in modern office buildings is responsible for a large part of the increase in electricity consumption in the world today (Barnham et al., 2006). In Fig. 5 the energy balance for heating is shown for the selected windows. In this case a positive value, as we can see for the south-facing window, means that the window leads to a net energy gain, i.e. more energy is gained through solar radiation during the heating season than what is lost through thermal conductance. As expected, the low-e windows are the best here due to the higher *g*-value. It can be seen that there is hardly any difference between the control strategies. This is as expected as the control strategies mainly affect the need for cooling.

3.2.3. Total energy balance

Since there is a need for both heating and a cooling in Stockholm the total energy balance, including both, is of

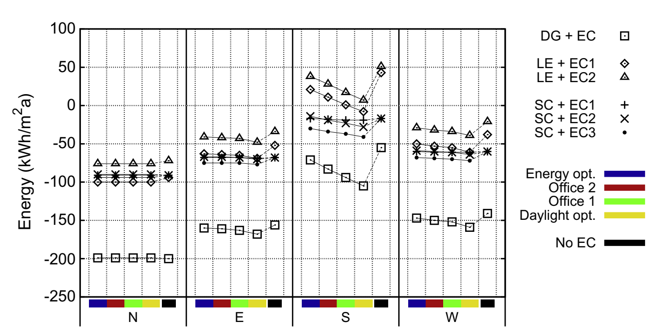

Fig. 5. Heating energy balance of the studied window combinations in Stockholm for different orientations.

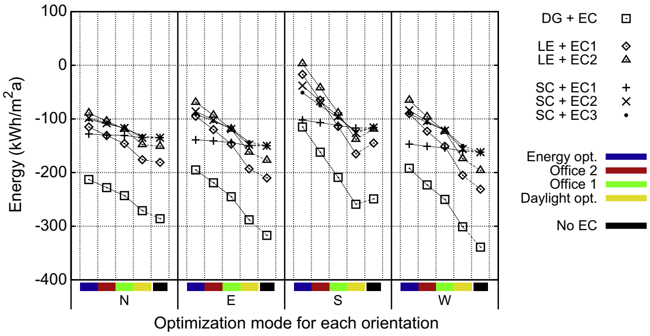

Fig. 6. Total energy balance of a window in Stockholm for different orientations.

interest. This is shown in Fig. 6, where it can be seen that in this case the low-e windows combined with EC coatings give the best performance.

When looking at the south-facing window only, Fig. 7, we can see that for daylight optimization the best window is the SC + EC1, but for all other control strategies the LE + EC2 is the best window combination.

The electrochromic windows always outperform the static ones for the "office 2" optimization mode, as shown in Fig. 8. For a south-facing window the decrease in energy need is of the order of 100 kWh/m^{2}a using smart windows instead of the static reference windows.

In Fig. 9 the EC combinations with solar control windows are shown to illustrate the dependence on the control strategy of the different windows. The SC + EC1 window is almost insensitive to the choice of control strategy with a difference of less than 20 kWh/m^{2}a between the two extreme cases, whereas the SC + EC2 and SC + EC3 combinations depend strongly on the control strategy with a difference of almost 100 kWh/m^{2}a. The reason is that the SC + EC1 combination is unfavorable and has a small difference in *g*-value between the low-transparent and the high-transparent states, as can be seen in Table 1.

Depending on the control strategy used and on the window orientation, different windows give the lowest total energy use. For the energy optimization mode the LE + EC2 window leads to the lowest energy need, but for the daylight optimization mode the SC + EC1 or SC + EC3 leads to the lowest total energy need, as can be seen in Fig. 10.

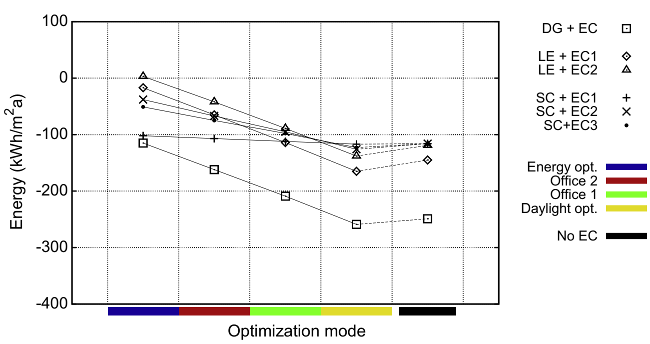

Fig. 7. Total energy balance for south-facing windows in Stockholm.

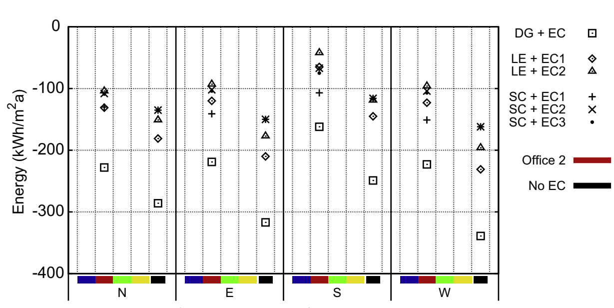

Fig. 8. Total energy balance of the investigated windows in Stockholm for different orientations, showing "office 2" optimization mode only together with the static windows.

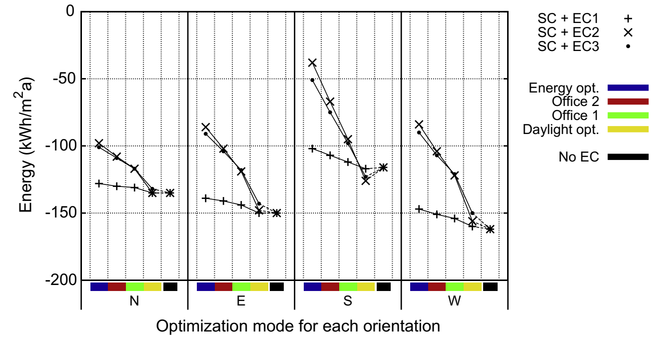

Fig. 9. Total energy balance of the solar control EC window combinations in Stockholm for different orientations.

3.3. Denver climate

3.3.1. Cooling energy balance

As Denver has both heating and cooling needs somewhere in between Stockholm and Miami, the annual need for cooling can be decreased by as much as 300 kWh per square meter window area by using a solar control or low-e coating in combination with an electrochromic layer instead of an uncoated double glazed window. As for the case of Stockholm it can be seen that the need for cooling

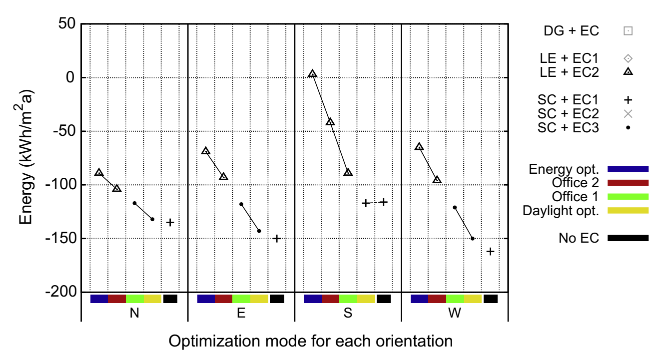

Fig. 10. Total energy balance of the selected windows in Stockholm for different orientations, showing only the best window combinations for each optimization mode.

is almost eliminated for the best window combinations with the optimum choice of control strategy. This is illustrated in Fig. 11.

3.3.2. Heating energy balance

For the heating balance, as can be seen in Fig. 12, the static low-e windows outperform the other window combinations. This is obviously due to the higher *g*-value of these windows and the fact that the Denver climate is characterized by cold winters but there is still a fair amount of solar radiation throughout the winter. The *g*-value is thus more important in Denver than in Stockholm, and all windows except the north-facing one contributes considerably to the heating balance. We can see that for the south-facing window with the highest solar irradiation, the control strategy actually also affects the heating energy balance. This is because there are periods also during the winter when the control system puts the window in a state which is not optimized for highest energy gain.

3.3.3. Total energy balance

For the total energy balance the cooling season becomes important and the best performing windows depend on the control strategy. In “energy optimization” mode the low-e EC combinations clearly outperform the others, as shown in Fig. 13.

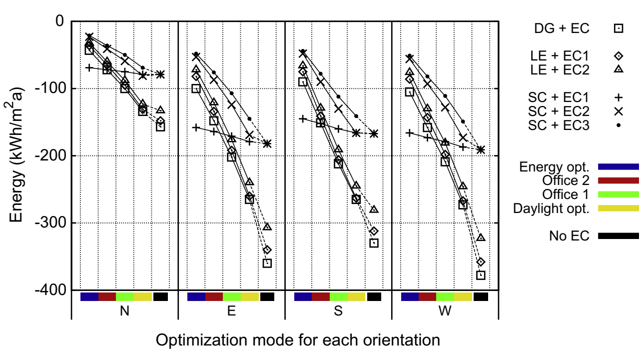

Fig. 11. Cooling energy balance of the selected window combinations in Denver for different orientations.

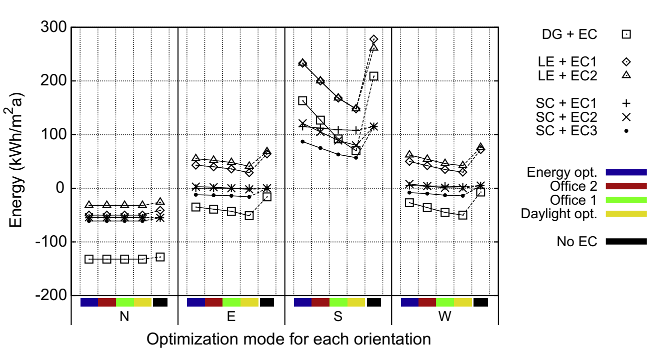

Fig. 12. Heating energy balance of the selected window combinations in Denver for different orientations.

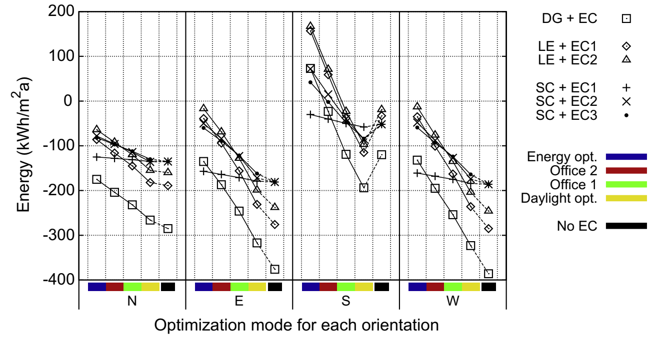

Fig. 13. Total energy balance of the selected windows in Denver for different orientations.

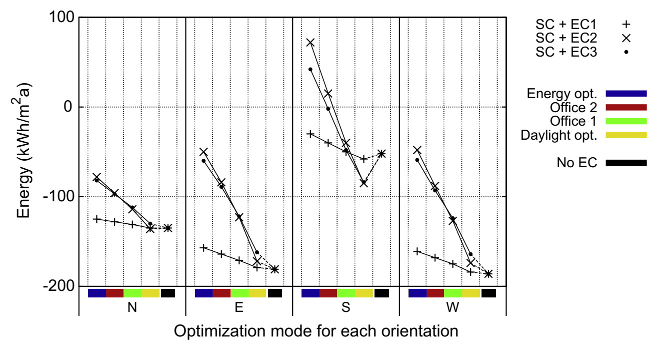

Fig. 14. Total energy balance of the solar control EC window combinations in Denver for different orientations.

In Fig. 14 only the solar control windows are shown. As for the case of Stockholm the graph shows that the importance of the control strategy is different for different windows. The control strategy is less important for the SC + EC1 window than for the other solar control EC window combinations.

The best windows for each of the control strategies are shown in Fig. 15. If we shift the control strategy from “office 1” to “office 2”, the window with the best energy performance facing north, east and west changes from SC + EC3 to LE + EC2. This clearly indicates the importance of considering different windows and different

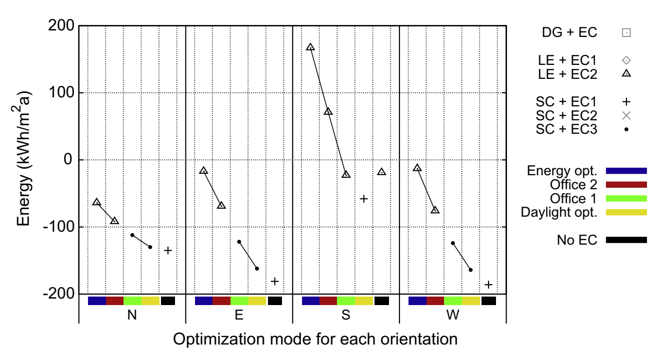

Fig. 15. Total energy balance of the windows with the best performance in Denver for different orientations.

control strategies for the EC windows depending on the building type and activity in the building.

3.4. Variation of the balance temperature

All the results so far have been obtained with the same building balance temperature. Because of different building standards in different parts of the world it is obviously not realistic to compare identical buildings in all climates. For the technique developed in this report it is very easy to vary the balance temperature. To illustrate the influence of the choice of balance temperature, this was varied between 2 °C and 14 °C in Stockholm. A balance temperature of 2° corresponds to a modern high standard office building while 14° is more typical for a residential block of flats.

3.4.1. Cooling energy balance

Generally the solar control combination outperforms the other switchable windows and the solar control reference 1 outperforms the other static windows as shown in Fig. 16. The largest potential for lowering cooling needs is in a building with a low balance temperature, since then the cooling season is longer. With a balance temperature of 14 °C there is hardly any cooling season in the Stockholm climate and all the window combinations have close to zero cooling needs.

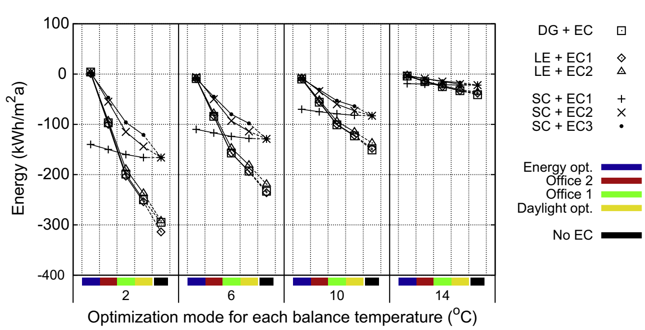

Fig. 16. Cooling energy balance of the selected window combinations in Stockholm for different heating balance temperatures and for a south-facing window.

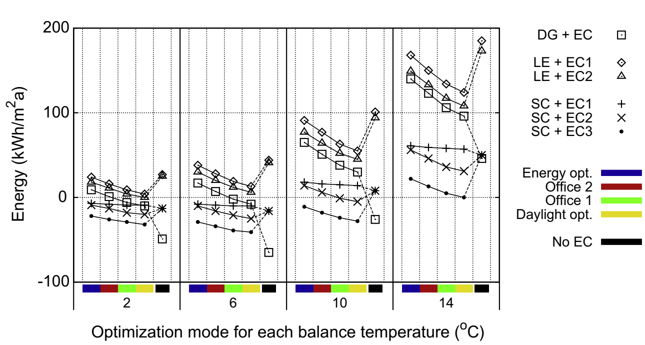

Fig. 17. Heating energy balance of the selected windows in Stockholm for different heating balance temperatures and for south-facing windows.

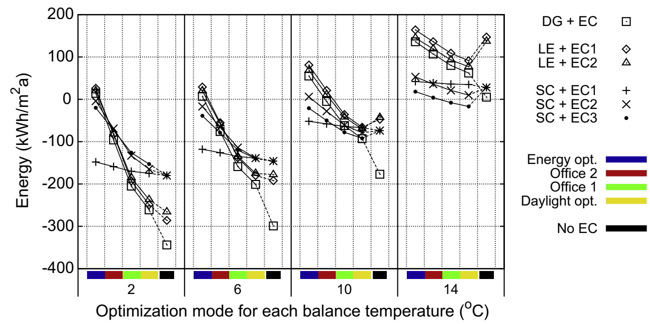

Fig. 18. Total energy balance of the selected windows in Stockholm for different heating balance temperatures and for south-facing windows.

3.4.2. Heating energy balance

For the heating energy balance the low-e windows yield the lowest heating energy needs as shown in Fig. 17. In this case almost all windows show a net energy gain and especially for the higher balance temperatures. A high balance temperature means a long heating season and also that the heating season includes periods with high solar irradiation.

3.4.3. Total energy balance

For the total energy balance in Fig. 18 the results depend strongly on the balance temperature. The largest differences between the different windows are in buildings with a low balance temperature. The control strategy also has largest influence in buildings with lower balance temperatures.

4. Conclusions

The emerging switchable window technology opens up the possibility of further improving the energy performance of the low-e and solar control glazing products available on the market today. At the same time this makes the choice of glazing combination for windows more complex and the energy balance calculations more difficult. This means there is a clear need for simplified but realistic energy balance simulation tools for windows, which can be used for different types of buildings in different climates, without having to perform complete building simulations.

In this paper we have taken two steps in this direction. We have used the Winsel window energy balance simulation tool and used simplified control strategies to illustrate that different window glazing combinations with and without electrochromic coatings can readily be compared and evaluated in different climates and for different types of buildings. The control strategies are very simple but we believe that the complexity of the real situation makes it necessary to use simplified models in order to compare the performance of different products. This is similar to the comparisons of the *g*- and *U*-values of windows. They are calculated according to a fixed set of conditions, although in a real situation both are functions of climate conditions.

In this investigation only the energy optimization strategy is completely unambiguous. It simply puts the electrochromic window in the state which minimizes energy consumption for heating and cooling. The other control strategies are strongly simplified, but for each of them it is possible to find a realistic setting of the key parameters, and they can all easily be set to different values in the software tool. An important factor to consider is presence detection. There is a considerable amount of energy to be saved if the control strategy switches to energy optimization as often as possible, i.e. when nobody is present in the office.

It is possible to achieve all window combinations used in this study using a combination of electrochromic coatings and existing low-e and solar control products. The values for the EC coatings were calculated and are not parameter values of existing products, but the chosen values are realistic and it is possible to achieve them with known technology. Selecting a suitable window combination based on electrochromic foil is not only about visual and energy performance. Durability is another important issue. Sensitive coatings should be put on protected surfaces, and the solar absorptance in the panes should be kept as low as possible to avoid heating of the panes. This is a factor that has not been considered in this study.

The daylighting aspect was simulated in the "daylight optimization mode", which is strongly simplified. There is certainly room for improvements in this respect and the energy used for artificial lighting was not included in the simulations. This study shows that a careful selection of glazing combinations and a thoroughly worked out control strategy is crucial for energy efficiency. A simplified simulation model can be a powerful tool for architects and building constructers in order to select the best windows and to meet the future needs for energy efficiency.

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References

Aleklett, K., Campbell, C., 2003. The peak and decline of world oil and gas production. Minerals & Energy-Raw Materials Report 18 (1), 5–20.

Assimakopoulos, M.N., Tsangrassoulis, A., Guarracino, G., Santamouris, M., 2004. Integrated energetic approach for a controlable electrochromic device. Energy and Buildings 36 (5), 415–422.

Barnham, K.W.J., Mazzer, M., Clive, B., 2006. Resolving the energy crisis: nuclear or photovoltaics? Nature Materials 5 (3), 161–164.

European Comittee for Standardization, En673:1998:glass in Building, Determination of Thermal Transmittance (*u* Value). Calculation Method, 1998.

Granqvist, C.G., 1995. Handbook of Inorganic Electrochromic Materials. Elsevier, Amsterdam.

International Organization for Standardization, Iso 9050:2003:glass in Building—Determination of Light Transmittance, Solar Direct Transmittance, Total Solar Energy Transmittance, Ultraviolet Transmittance and Related Glazing Factors, 2003.

Karlsson, J., 2001. Control System and Energy Saving Potential for Switchable Windows. Rio de Janeiro, Brazil.

Karlsson, J., Karlsson, B., Roos, A., 2001. A simple model for assessing the energy performance of windows. Energy and Buildings 33 (7), 641–651.

Lee, E.S., Tavil, A., 2007. Energy and visual comfort performance of electrochromic windows with overhangs. Building and Environment 42 (6), 2439–2449.

Meteotest, Meteonorm 5.0 Global Meteorological Database for Solar Energy and Applied Meteorology, 2003.

United Nations Environment Programme, Buildings and Climate Change—Status, Challenges and Opportunities, 2007.

Windows Daylighting Group—Lawrence Berkeley National Laboratory, Chromogenic Materials—Optical Constants of Electrochromic Materials and Transparent Conductors, 2009.